Can Ecological Engineering Redefine Wetland Recovery in Mining?

Yolandi Schoeman[1,2], Paul Johan Oberholster[1,2]

[1]*Centre for Mineral Biogeochemistry, University of the Free State, P.O. Box 339, Bloemfontein, 9300, South Africa, SchoemanY1@ufs.ac.za (ORCID 0000-0002-5844-059X), OberholsterPJ@ufs.ac.za (0000-0001-5369-4497)*

[2]*Ecological Engineering Institute of Africa, University of the Free State, P.O. Box 339, Bloemfontein, 9300, South Africa*

Abstract

Wetlands altered by mining provide critical services such as water purification, biodiversity support, and flood regulation, yet traditional monitoring tools inadequately capture interactions in these altered ecosystems. This study presents an innovative framework integrating the Ecological Integrity Index and Ecological Engineering Index to assess and guide ecological recovery. Applied at the Leeuspruit wetland near Gold Fields South Deep Gold Mine, the indices identified key areas for intervention. Findings revealed severe degradation, with elevated uranium and Total Dissolved Solid levels. Proposed interventions, including hybrid constructed wetlands and bioremediation, aim to enhance biodiversity and water quality. This framework offers a replicable model for sustainable mining wetland restoration globally.

Keywords: Ecological engineering, wetland restoration, ecosystem health, mining wetlands, sustainability monitoring

Introduction

Mining activities can substantially alter wetland ecosystems, reducing their ability to provide critical services such as water purification, flood regulation, and biodiversity support (Belle *et al*. 2023; Schoeman *et al*. 2025). Traditional monitoring approaches often fail to account for the interactions between natural and engineered systems, hindering effective restoration efforts. Ecological engineering provides a structured framework for addressing these challenges through targeted interventions (Jansen van Vuuren *et al*. 2024).

This study integrates the Ecological Integrity Index (EII), Ecological Engineering Index (EEI), and Ecological Engineering Nexus Accounting Framework (EENAF) to guide wetland recovery strategies. By incorporating financial valuation, the framework demonstrates how ecological improvements can support both environmental sustainability and economic decision-making.

Methods

To develop a comprehensive framework for wetland recovery, a combination of ecological and engineering assessment tools was applied. The approach involves evaluating baseline ecological conditions using the EII and identifying potential improvements through the Ecological Engineering Index EEI. This dual-index system provides a structured pathway for planning and prioritizing interventions based on both ecological and operational needs. The framework is further strengthened by the integration of financial and ecosystem service valuation under the EENAF, allowing stakeholders to link ecological outcomes with long-term sustainability and economic feasibility.

The Ecosystem Condition Index (ECI) is the computational core of the Ecological Integrity Index (EII). While the EII represents the broader conceptual framework that includes metric selection, weighting, and interpretation, the ECI provides the quantitative calculation that produces the final ecological condition score used within the EII.

Ecological Integrity Index (EII)

The Ecological Integrity Index (EII) is a composite assessment tool that evaluates the current ecological state of wetland ecosystems using a weighted metric system. It provides an overall ecological health score by combining scores from key biophysical indicators such as biodiversity, water quality, soil health, and hydrological connectivity.

A key component of the EII is the Ecosystem Condition Index (ECI), which aggregates individual metric scores into a single value using a weighted average approach, as shown in the equation below:

$$ECI = \frac{\sum_{i=1}^{n} Wi \, . Ni}{\sum_{i=1}^{n} Wi}$$

Where:

- N_i is the score for metric i ,
- W_i is the assigned weight for metric i,
- n is the total number of metrics.

To explain further, in this equation, (Ni) refers to the measured score of the ecological metric (i), not to be confused with the number of metrics, which is denoted by (n). This distinction is important to avoid misinterpretation: (Ni) represents the actual ecological condition of a specific parameter (e.g., water quality, biodiversity), while (n) indicates the total number of such parameters included in the calculation.

The EII evaluates the current ecological state of wetland ecosystems by analyzing critical biophysical metrics. Biodiversity is a key indicator, reflecting the ecosystem's resilience and ability to provide services through species richness, keystone species presence, and the effect of invasive species. A diverse biological community supports stability and enhances natural recovery processes. Water quality measures, including uranium concentration, total dissolved solids (TDS), and nutrient loads, indicate pollution levels and inform priorities for remediation efforts. Soil health is assessed via organic matter content and erosion rates, both of which influence nutrient cycling and support for vegetation. Finally, hydrological connectivity measures flow continuity and retention capacity, critical factors for maintaining wetland functionality and mitigating the risks of habitat fragmentation. Together, these metrics guide targeted interventions by identifying areas of vulnerability and potential ecological enhancement.

To clarify for general readers, the Ecological Engineering Index (EEI) uses Normalized Improvement (*NI*) as its core computational tool. While EEI is a broader decision-making framework evaluating the potential effectiveness of various ecological interventions, NI quantifies how much improvement a specific intervention could produce relative to baseline and target values.

Ecological Engineering Index (EEI)

The Ecological Engineering Index (EEI) is a decision-support tool designed to evaluate the effectiveness of proposed ecological interventions. It builds upon the EII by projecting how each intervention is expected to improve the current ecological metrics. The EEI is guided by ecological engineering principles (Schoeman *et al.* 2025) such as ecosystem connectivity, self-sustainability, energy efficiency, and resilience.

A central part of the EEI is the Normalized Improvement (NI) calculation, which quantifies how much a specific ecological metric is expected to improve due to a given intervention. This allows direct comparison of potential interventions. NI is calculated as follows:

$$NI = \frac{M(post) - M(baseline)}{M(target) - M(baseline)}$$

Where:

- $M_{baseline}$ is the initial condition of the metric,
- M_{post} is the expected value after intervention,
- M_{target} is the defined goal or optimal ecological condition.

NI results are then used within the EEI framework to prioritize interventions based on the degree of projected ecological improvement, adherence to design principles, and practical feasibility.

The EEI (Schoeman & Oberholster, 2024a) assesses the effectiveness of ecological interventions by projecting improvements in key metrics and aligning solutions with core ecological engineering principles. These include ecosystem connectivity, energy efficiency, resilience, and self-sustaining design (Schoeman *et al.* 2025). Constructed wetlands are selected to reduce pollutants and enhance biodiversity through natural processes like sedimentation and microbial uptake. Riparian buffers stabilize soils and support habitat continuity, while bioremediation targets pollutant breakdown using microbial activity. By grounding interventions in these principles, the EEI supports both immediate recovery and long-term ecosystem resilience.

Intervention Design

The intervention design at Leeuspruit was developed based on the EEI, which identified critical ecological deficits in water quality, biodiversity, and hydrological connectivity. Constructed wetlands were recommended to be implemented to reduce elevated uranium and TDS by enhancing natural filtration processes and nutrient cycling. Riparian buffer zones were recommended to be established to stabilize soils, mitigate erosion, and provide habitat corridors to promote biodiversity recovery. Bioremediation techniques were recommended to be applied where microbial processes could degrade pollutants effectively, improving both soil and water quality. These proposed interventions, aligned with ecological engineering principles, can address immediate restoration needs while enhancing long-term ecosystem resilience.

Integration with EENAF

The EENAF (Schoeman & Oberholster, 2024b) provides a structured approach to link ecological recovery efforts with financial and socio-economic outcomes. It achieves this through three key components:

- The Extent and Condition Accounts document changes in wetland area and ecological state, helping stakeholders assess the physical improvements resulting from restoration interventions. This data enables long-term tracking of ecosystem health and capacity for service provision.
- The Service Flow Accounts measure the ongoing performance of ecosystem services such as water purification, carbon sequestration, and flood mitigation. These services are vital for both environmental sustainability and human well-being, providing measurable indicators of ecological functionality.
- Finally, the Monetary Valuation component translates improvements in ecosystem services into economic terms.

This component supports investment decisions, regulatory compliance, and sustainability reporting by assigning financial value to these benefits. This valuation helps stakeholders justify ecological interventions by demonstrating clear returns on investment (ROI), enhancing business cases for continued environmental stewardship and project funding.

Results and Discussion

Interpretation of ECI Scores

To aid interpretation of calculated ECI values, a standardized classification system is used to link ECI with ecological condition categories (Tab.1). These categories reflect levels of ecosystem modification and functionality, ranging from natural (Category A–B) to critically degraded (Category F). This classification is adapted from ecological benchmarking systems such as WET-Health guidelines, and provides a transparent basis

Table 1 *Ecosystem Condition Index (ECI) and EII Score Interpretation.*

ECI Score	EII Category	Interpretation
0.80–1.00	A–B	Natural or near-natural ecosystem
0.60–0.79	C	Slightly modified; functioning mostly intact
0.40–0.59	D	Moderately degraded; impaired but restorable
0.20–0.39	E	Seriously modified; high loss of ecological value
0.00–0.19	F	Critically degraded; ecosystem collapse

Table 2 Baseline conditions and projected improvements.

Key metric	Baseline value	Target value	Projected value	Normalized improvement (%)
Uranium concentration	0.09 mg/L	0.03 mg/L	0.045 mg/L	66.67
Total dissolved solids	950 mg/L	500 mg/L	600 mg/L	70.00
Biodiversity score	0.2	0.8	0.6	75.00
Vegetation coverage	0.4	0.8	0.7	60.00
Hydrological and terrestrial connectivity	0.3	1.0	0.8	83.33

for evaluating the severity of degradation and prioritizing restoration actions.

Baseline Assessment

The EII assessment classified the Leeuspruit wetland as seriously modified (Category E). Key findings include:

- Uranium concentration: 0.09 mg/L, exceeding safe thresholds.
- TDS: 950 mg/L, indicating severe mineral pollution.
- Biodiversity: Dominance of invasive species with reduced native species richness.
- Hydrological connectivity: Disrupted flow patterns due to mining infrastructure.

Projected Outcomes

Tab. 2 summarizes baseline conditions, target goals, and projected improvements based on EEI assessments.

Range and Outcomes for the EEI

The EEI serves as a predictive decision-support tool, guiding the prioritization of ecological engineered interventions based on projected ecological gains. It operates through the NI metric, which evaluates how much improvement an intervention is expected to deliver relative to a desired target. The EEI framework enables stakeholders to assess the effectiveness of proposed ecological engineering solutions, helping to strategically allocate resources. The classification table below outlines the range of EEI/NI scores and their associated outcomes, from highly effective interventions to those with minimal return.

The ecological engineering approach (Fig. 1) applied at Leeuspruit is designed to transform the degraded wetland into a resilient post-mining futures zone. Phased interventions focus on adaptive hydrological modeling and integrated ecological monitoring to ensure long-term functionality. A dual remediation strategy – combining phycoremediation and phytoremediation – is proposed alongside compact hybrid constructed wetlands in key buffer zones. These solutions align with broader sustainability goals by promoting carbon sequestration, biodiversity conservation, and landscape connectivity. With EEI/NI scores ranging from 0.60 to 0.80, the proposed interventions indicate substantial potential for ecological recovery. Additionally, the ability to generate over USD 1.08 million annually from ecosystem services highlights the financial viability of these actions, linking ecological restoration with carbon and biodiversity market opportunities.

***Table 3** Ecological Engineering Index (EEI) Score Interpretation.*

EEI / NI Score	Projected outcome	Intervention priority
0.80–1.00	High potential for full functional recovery	Highest priority intervention
0.60–0.79	Good improvement expected	Recommended for scaling
0.40–0.59	Moderate improvement	Consider with other options
0.20–0.39	Limited gains	Low return, limited impact
0.00–0.19	Very low effectiveness	Not suitable / low priority

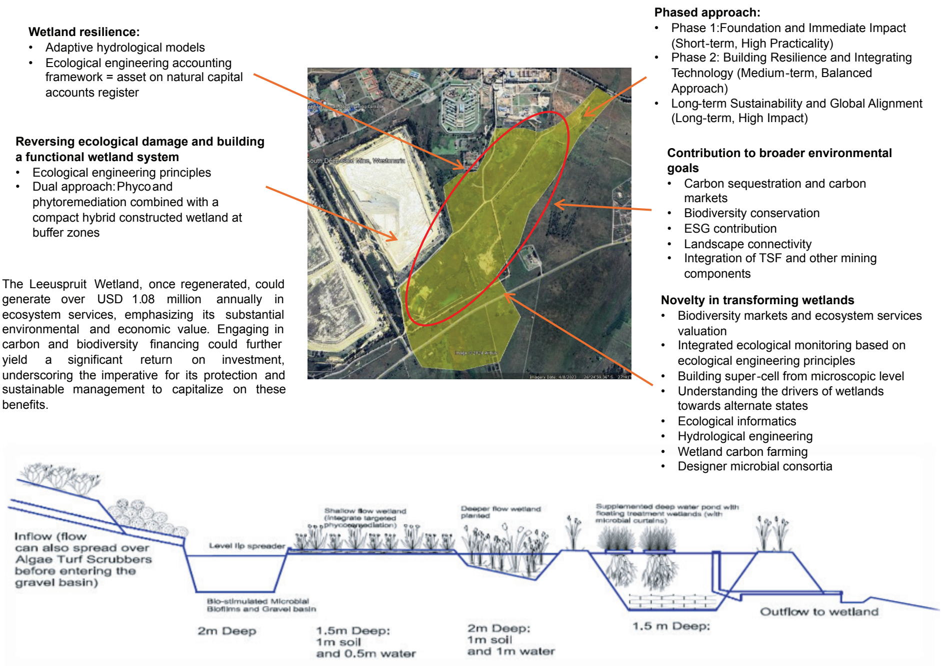

***Figure 1** Ecological engineering approach to redefine wetland recovery (Schoeman & Oberholster, 2024c).*

Financial Valuation and Project Support

The financial evaluation using the EENAF highlights the economic viability of restoring the Leeuspruit wetland. Estimated annual savings include USD 500,000 from reduced water treatment costs, USD 200,000 from erosion control and vegetation recovery, and revenue potential from carbon credits, with approximately 1,200 tonnes of CO_2 equivalent offset annually. Additionally, improved hydrological connectivity is expected to lower flood-related infrastructure maintenance costs. The site also holds the potential for participation in emerging biodiversity credit and market schemes, further enhancing its long-term ecological and financial value. These outcomes present a compelling return on investment (ROI), strengthening the case for funding ecological interventions and positioning mining operations as leaders in sustainability and compliance.

Conclusion

This study demonstrates the potential for integrating the Ecological Integrity Index, Ecological Engineering Index, and Ecological Engineering Nexus Accounting Framework to redefine wetland recovery strategies in mining contexts. By linking ecological and financial metrics, the framework supports both environmental sustainability and economic decision-making.

The Leeuspruit case study highlights that targeted interventions can improve ecosystem functionality while reducing long-term operational risks. This integrated approach provides a replicable model for global wetland recovery in mining-altered landscapes, aligning with sustainability and biodiversity conservation goals.

Future research should explore refining these indices and extending financial valuation models to other ecosystems and industrial contexts.

Acknowledgments

The authors would like to thank Gold Fields South Deep Gold Mine for their support and collaboration in this project.

References

Belle G, Schoeman Y, Oberholster PJ (2023) Potential toxic element pollution in surface water and its implications for aquatic and human health: Source-Pathway-Receptor Model. Water 15:3100. doi:10.3390/w15173100

Jansen van Vuuren M, Schoeman Y, Botha AM, Oberholster PJ (2024) Revealing the protective dynamics of an ecologically engineered wetland against acid mine drainage: A case study in South Africa. Appl Sci 14:7441. doi:10.3390/app14177441

Oberholster PJ, Schoeman Y, Truter JC, Botha AM (2022) Using periphyton assemblage and water quality variables to assess the ecological recovery of an ecologically engineered wetland receiving acid mine drainage before and after a dry spell. Processes 10:1–22. doi:10.3390/pr10010001

Schoeman Y, Erasmus M, Naidoo N, Oberholster PJ (2025) Novel hybrid nature-based solutions for the sustainable treatment of industrial wastewater: alkaline and acid mine drainage. In: Fosso-Kankeu E, Masindi V, Maree J, Mamba B (Eds), Customized technologies for sustainable management of industrial wastewater: Circular economy approach. Scrivener Publishing, p 39–110 (In Press)

Schoeman Y, Oberholster PJ (2024a) Special session presentation: Bridging the gap: Ecological Engineering Index for enhanced monitoring of nature-based and ecologically engineered systems. 25th Waternet/WARFSA/GWP-SA Symposium, 30 Oct–1 Nov 2024, Maseru, Lesotho

Schoeman Y, Oberholster PJ (2024b) Advancing mining sustainability metrics: The Ecological Engineering Nexus Accounting Framework (EENAF). In: Das AP, Van Hullebusch ED, Akcil A (Eds), Sustainable management of mining waste and tailings: A circular economy approach. CRC Press

Schoeman Y, Oberholster PJ (2024c) Pre-feasibility study for optimizing the Leeuspruit wetland area at South Deep Gold Mine. Unpublished Report. UFS:Bloemfontein.